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ERROR PATTERNS AND BLOCK CODING FOR THE DIGITAL HIGH-SPEED AUTOVON CHANNEL

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Voice telephone systems, such as AUTOVON, are currently being used for the transmission of high-speed digital data. AUTOVON's performance in passing 4800 b/s and 9600 b/s digital data via the state-of-the-art Codex 9600 modem is adequate to support channel bit error rates in the order of 10^{-4} to 10^{-5}. Additionally,

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) it is demonstrated that the errors occur in bursts of lengths and densities such that block coding for error correction would require the use of a large number of parity bits per block (approximately 90% parity for full error correction). Improvement factors of two orders of magnitude in block error rate, at 50% parity, can be achieved.

ACKNOWLEDGMENT

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INTRODUCTION

In recent years there has been, within both the civil and military environments, a trend toward the use of voice grade circuits (nominally 2400 Hz of usable bandwidth) for high-speed digital data transmission. This trend has developed because of the need to interconnect computers and computer-like devices on existing communications circuits at data rates sufficiently high for the achievement of operational computer efficiency. A natural outgrowth of efforts in this direction is the use of the common-user voice grade circuits of the Defense Communication Agency's AUTOVON for digital data transmission at the state-of-the-art speed of 9600 b/s.

The Electronic Systems Division of the Air Force is presently developing (in conjunction with the Strategic Air Command (SAC) and MITRE) a new continental U.S. record data communications system for SAC called the SAC Automated Total Information Network, SATIN IV. Since AUTOVON is the primary candidate for use as the backbone transmission facility for SATIN IV, a study was undertaken to determine the digital characteristics of AUTOVON. As a first step in this study, digital error patterns were measured on AUTOVON circuits and analyzed and used as an aid in designing error control techniques to provide the high-degree of accuracy required for reliable data transmission.

In this paper, the error patterns are described and the performance of one forward error control technique (block coding) is evaluated. It is demonstrated that forward error correction using block coding techniques leaves less than 20% of the available channel capacity to be used for information and is, therefore, impractical for SATIN IV.

SECTION II

AUTOVON CHANNEL TESTS

AUTOVON

AUTOVON is basically a network of voice grade wireline circuits and microwave links crisscrossing the United States in the same fashion as the commercial telephone system. Its use is limited to authorized agencies of the United States Government. The network contains switches (i. e. , ESS and CROSSBAR) of the same type as commercial communications. These switches provide the call routing and interconnection functions of AUTOVON. The network is made up of unconditioned Common Grade [1] Leased Lines. The performance of AUTOVON circuits when used for digital data transmission is related to amplitude and phase distortion, channel noise and phase jitter, and the manner in which the decision algorithm of the data transmission modem responds to these channel conditions. Thus, the true digital data channel is not AUTOVON alone, but rather AUTOVON in conjunction with the modem used. The modem utilized for the channel tests reported herein was the Codex 9600 modem. This modem was chosen because it was the only on-hand government-owned 9600 b/s telephone line data modem available at the test site during the test period.

The Codex 9600 modem is designed to transmit 4800, 7200, or 9600 b/s serial, synchronous digital data at a 2400 baud signaling rate over a dedicated type 3002, C-2 conditioned, 4-wire telephone circuit. It is a full-duplex, double-sideband, suppressed-carrier modem using a combination of amplitude-and phase-shift keying with transversal filter equalization. The transmitted signal occupies a 2400 Hz spectrum centered at 1706 Hz. Each baud contains information either from a 4-bit sample of 9600 b/s, a 3-bit sample of 7200 b/s, or a 2-bit sample of 4800 b/s input data. Input data is scrambled before transmission to prevent the receiver from becoming sensitive to data patterns and to provide a uniform line-signal spectrum for the equalization process. Receiver-carrier and timing-recovery circuits use information contained in the transmitted data to eliminate the need for transmission of pilot tones.

Test Procedure

The AUTOVON performance was measured by establishing a communication facility and transmitting test telephone calls through the Codex 9600 modem. When the signal was received by the receive modem, decisions as to bit values were made and the received bit sequence (suitably delayed to account for transmission delay) was added modulo 2, with no carry, to the transmitted sequence. This summation (a bit-by-bit error pattern) was then recorded on computer compatible magnetic tape in a suitable format for later statistical analysis. Although dialing for call connections was to target switches, the trunks were randomly selected by the inherent nature of call dialing.

In all cases, data transmission originated at the Rome Air Development Center (RADC), Griffiss AFB, N. Y., and proceeded via C-3 conditioned access lines to the Tully, N. Y., AUTOVON switch. From Tully, connections were made to the switches at Pottstown, PA., Arlington, VA., Rockdale, GA., and Santa Rosa, CA. (in varying orders and combinations). The return connection was back to RADC via Tully. Of these switches, only Arlington, VA. was an ESS.

Data Sample Size

The digital data error patterns were collected by transmitting test calls of one-half to one hour duration on AUTOVON. A total of over 3 billion bits was collected at 4800 b/s and almost 4 billion bits were collected at 9600 b/s. This data sample is summarized in Table I.

Table I

Data Summary – All Data

Data Rate	Total Bits	Total Errors	Bit Error Rate
4800 b/s	3,074,760,833	129,742	4.3×10^{-5}
9600 b/s	3,996,064,721	325,130	8.1×10^{-5}

As can be seen in Figure 1, the predominate type of error at 4800 b/s is the single error. At 9600 b/s, while single errors still predominate, double errors are nearly as common.

The distribution of error-free intervals (the probability that a gap between errors is equal to or longer than the abscissa value as presented in Figure 2) is indicative of the complexity of the data channel. A large number of intervals in the range of zero to thirty bits are usually seen on microwave circuits (62% of the U.S. telephone system) and are indicative of short dense bursts. When long intervals predominate (thousands of bits), the channel is random with a bit error rate which is approximately the inverse of the mean interval length. As can be seen in Figure 2, the AUTOVON channel is very complex. There are microwave type short intervals and more random error-related long intervals.

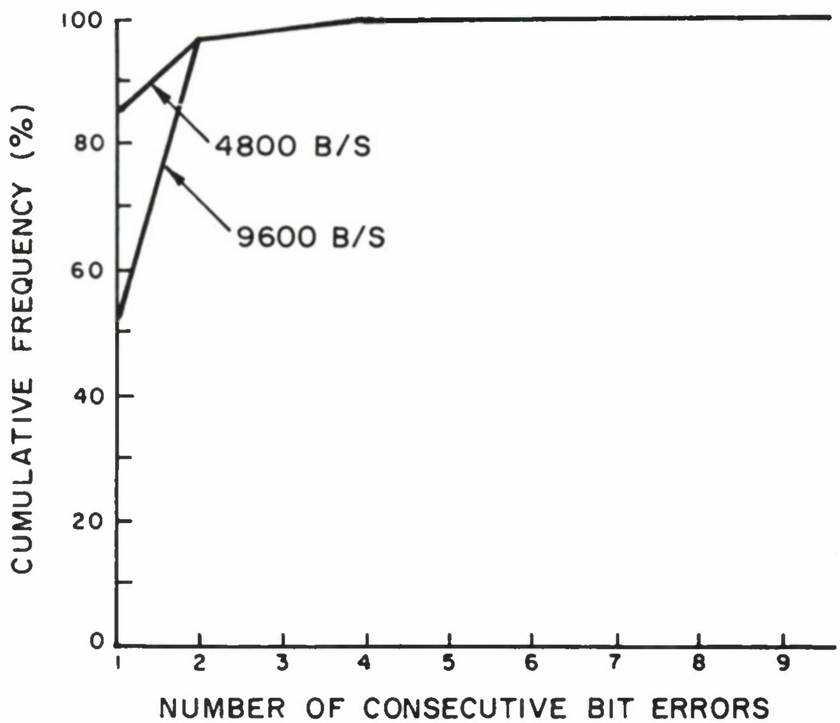

Figure 1. Cumulative Distribution of Consecutive Errors

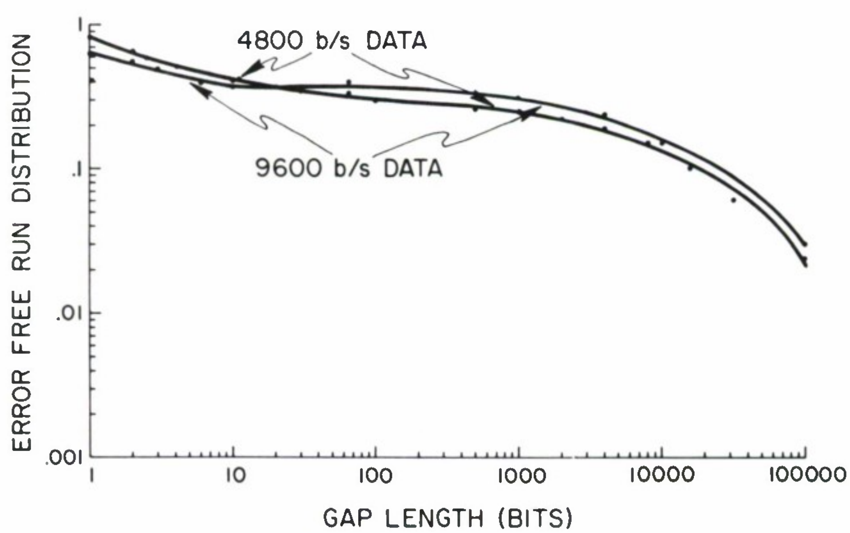

Figure 2. Error-Free Interval Distribution

Figures 3 and 4 examplify an interesting characteristic of the signaling structure of the Codex modem; that is, when errors occur, they tend to occur in even numbers. This shows up for a large range of numbers of errors in a block at 4800 b/s. At 9600 b/s, fully 70% of the blocks with errors will have either two or four errors. This characteristic makes the Codex modem/AUTOVON channel a difficult one to apply forward-error correction to because most coding techniques depend on some form of majority logic scheme for their success.

The most commonly used error probabilities in the design of error control coding systems (forward error correction or retransmission) are the probabilities of at least E errors in an M bit block. For any value of M, the probability of at least one error is the block retransmission rate for a retransmission system (assuming perfect error detection) and the uncorrected block error rate for a forward error correction system. For a code that detects (or corrects) E-1 errors in an M bit block, the probability of at least E errors is the post-detection (or correction) block error rate. In Figures 5 and 6, these probabilities are presented for a wide range of block lengths and error values. The block error rate is generally no more than one-half order of magnitude higher at 9600 b/s than at 4800 b/s. The shapes of the curves are essentially the same for all values displayed, and it can be concluded that in a system that uses error control (of some type), a design developed from the 9600 b/s results would give the same or better performance at 4800 b/s.

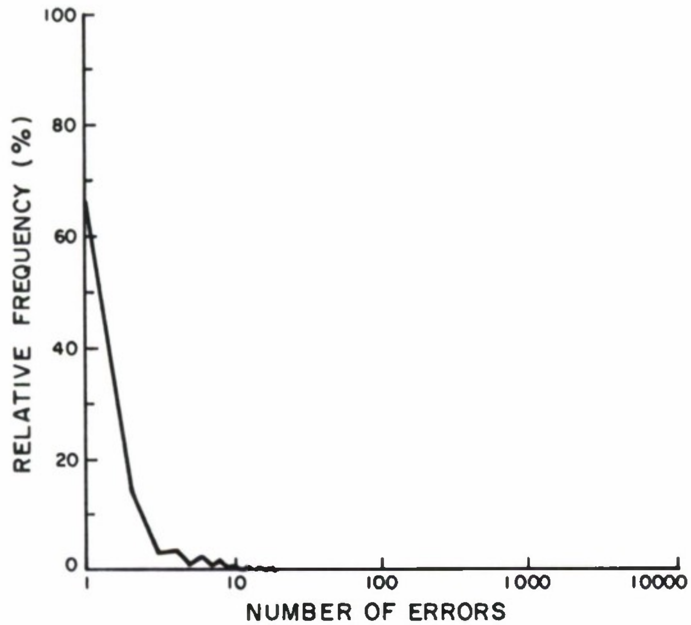

Figure 3. Relative Frequency of Errors – 4800 b/s, 2048 Bits/Block

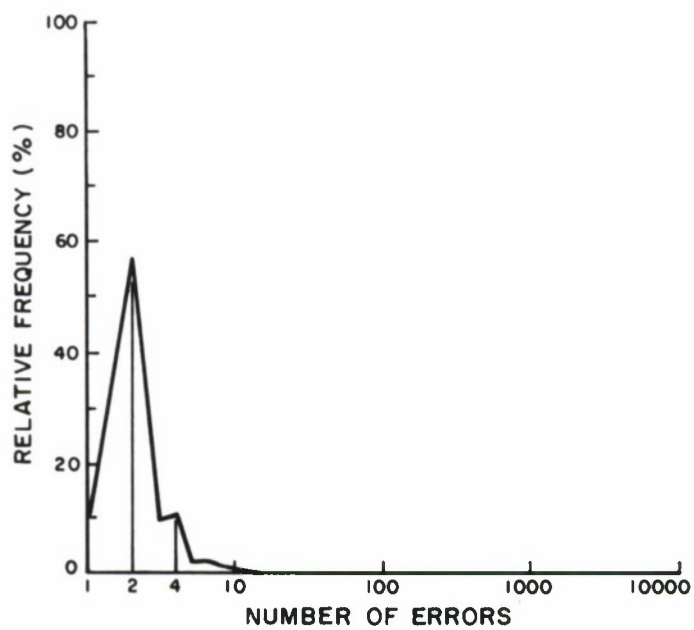

Figure 4. Relative Frequency of Errors – 9600 b/s, 2048 Bits/Block

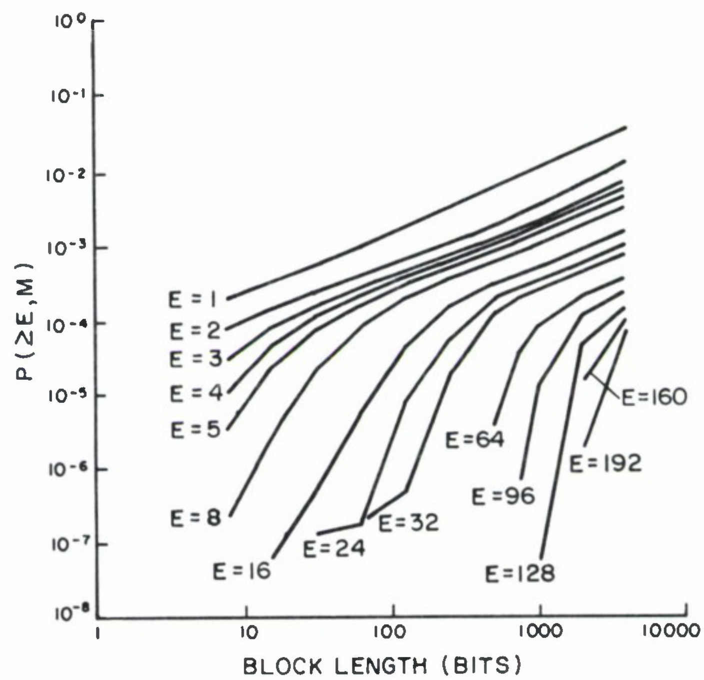

Figure 5. Probability of at Least E Errors in an M Bit Block — 4800 b/s Data

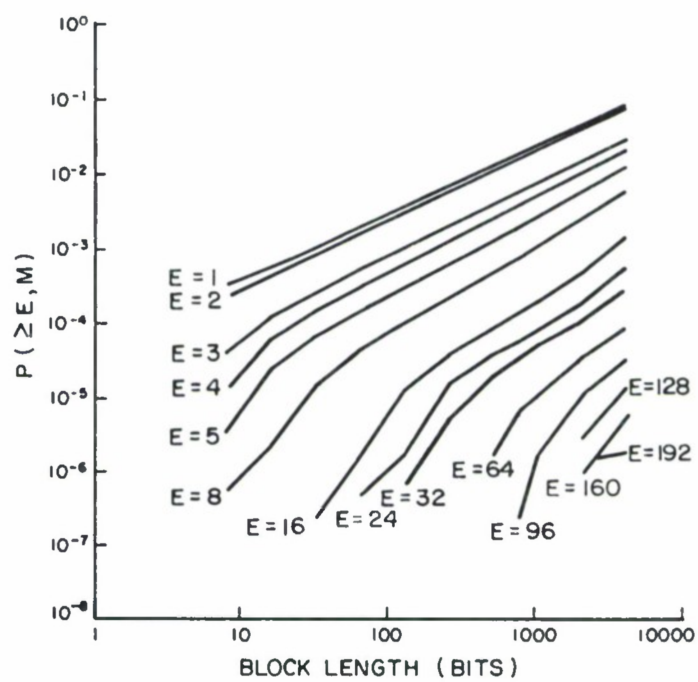

Figure 6. Probability of at Least E Errors in an M Bit Block — 9600 b/s Data

SECTION III

BURST DEFINITIONS

The previous discussion of error pattern distributions does not present the complete picture. Visual examination of tables showing the errors indicates that they occur in bursts. The previous distributions give no information about length of bursts, nor is there information relative to the interval between bursts (guard space). For this reason, the data shall be evaluated in terms of burst distributions.

Definition of a Burst

A burst is defined as a region of the serial data stream where the following properties hold. A minimum number of errors, M_e, are contained in the region and the minimum density of errors in the region is Δ. Both of these conditions must be satisfied for the chosen values of M_e and Δ for the region to be defined as a burst. The density of errors is defined as the ratio of bits-in-error to the total number of bits in the region.

The following properties hold for the burst. The burst always begins with a bit-in-error and ends with a bit-in-error. A burst may contain correct bits. Each burst is immediately preceded and followed by an interval in which the density of errors is less than Δ.

The burst probability density function is defined as the probability of occurrence of a burst of length N where N is any positive integer. The burst length is measured in terms of the total number of bits in the burst. A separate burst probability density function may be determined for each pair of Δ and M_e values.

The minimum number of errors in a burst has been chosen to be two for all the data included here. Experience [2] indicates that larger values of M_e would not change the values of burst length significantly. When a value of one is selected for M_e, every error becomes a burst and the requirement that a burst begin and end in different errors is violated. Consequently, the burst distribution reduces to the consecutive error distribution. While a minimum value Δ is used in defining bursts, the actual burst error density is calculated and the algorithm that applies the definition to the data has the effect of maximizing this error density.

Definition of an Interval

The interval is defined as the region, bounded by correct bits, in the serial data stream where the following property holds. The maximum density of errors in the interval is less than Δ. An interval may contain errors and is always immediately preceded and followed by a burst. Thus, each and every bit in the data stream must lie in either a burst region or an interval region.

The interval probability density function is defined as the probability of occurrence of an interval of length L, where L is any positive integer. The interval probability density is a joint function of both Δ and M_e. Use of $M_e = 1$ has the effect of reducing the interval distribution to the error-free interval distribution. The guard space ratio is defined as the ratio of an interval length to the burst length preceding it.

SECTION IV

BURST ANALYSIS

Burst Distributions

Examining the burst distribution functions in Figure 7, it is evident that errors generally occur in bursts of less than 1000 bits duration. The 4800 b/s channel exhibits bursts that are almost one order of magnitude shorter than those of the 9600 b/s channel for the same cumulative frequency. The 9600 b/s bursts are both longer than those at 4800 and denser in errors (Figure 8).

Interval Distributions

Intervals between bursts are generally very long at either data rate (Figure 9) and a greater percentage of the intervals, 90% versus 83%, are error-free (Figure 10) at 4800 b/s than at 9600 b/s; that is when random errors between bursts occur, they are more likely to occur at 9600 b/s than at 4800 b/s. The exact relationship of bursts and intervals is shown in Figure 11, from which it can be seen that a burst at 4800 b/s is followed by a longer interval than one at 9600 b/s. This result is very important for forward error correction systems since about 6% of the bursts cannot be randomized by interleaving due to the insufficiently long (less than 3 times burst length) following interval.

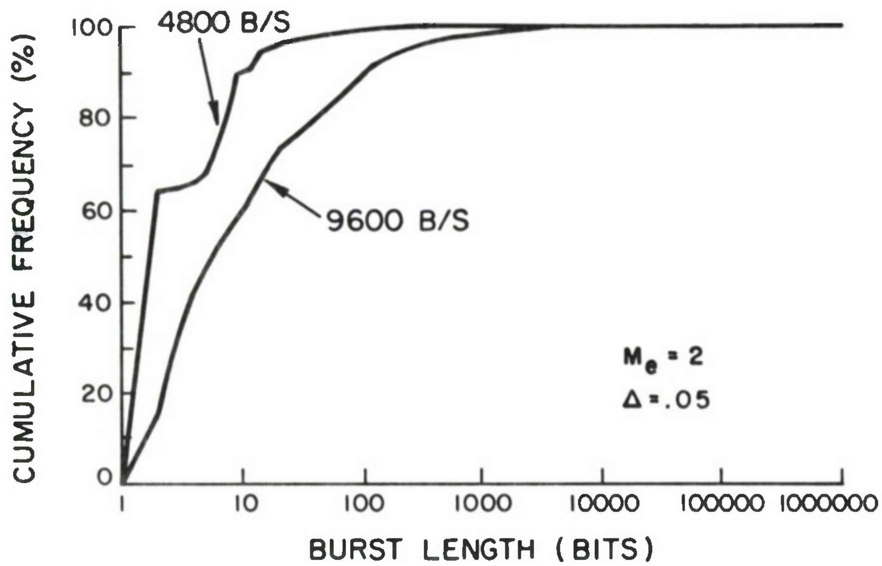

Figure 7. Cumulative Distribution of Burst Lengths

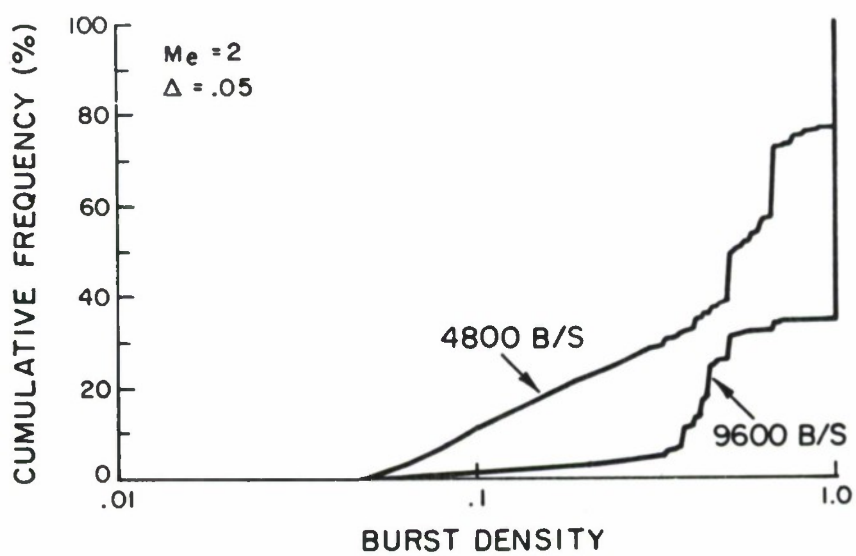

Figure 8. Cumulative Distribution of Burst Densities

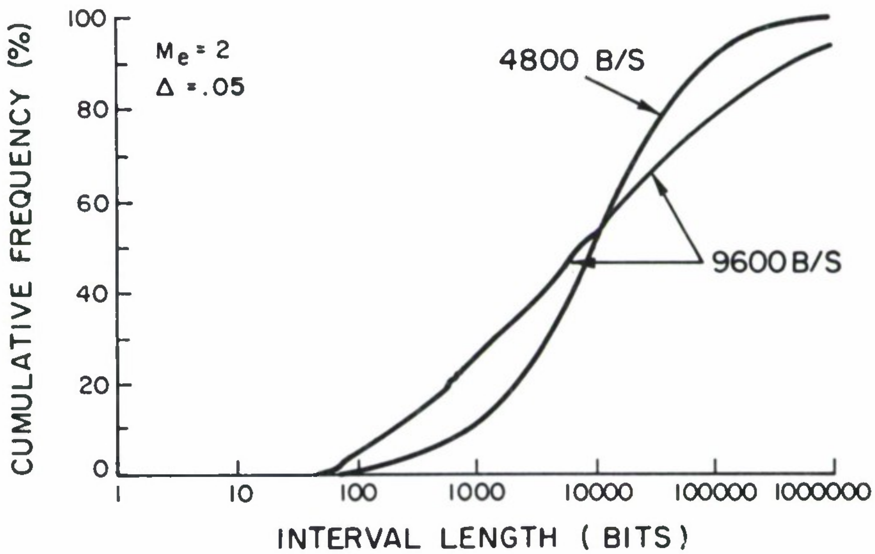

Figure 9. Cumulative Distribution of Interval Lengths

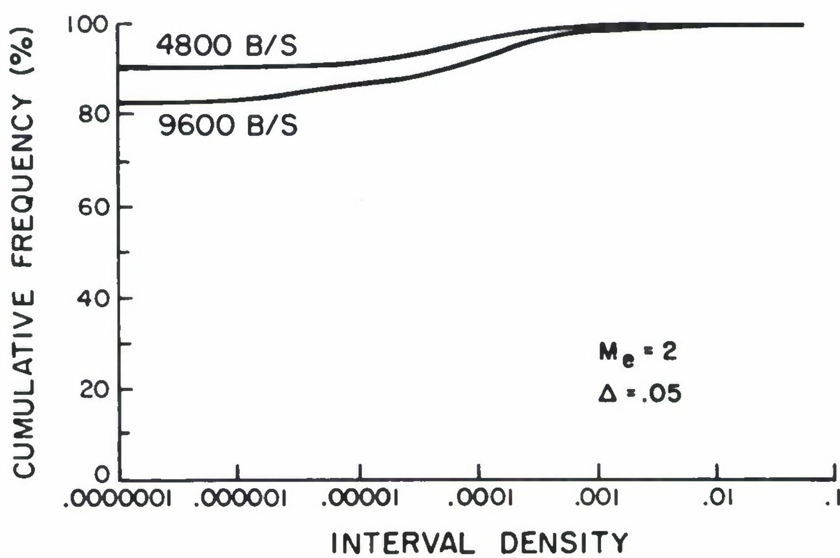

Figure 10. Cumulative Distribution of Interval Densities

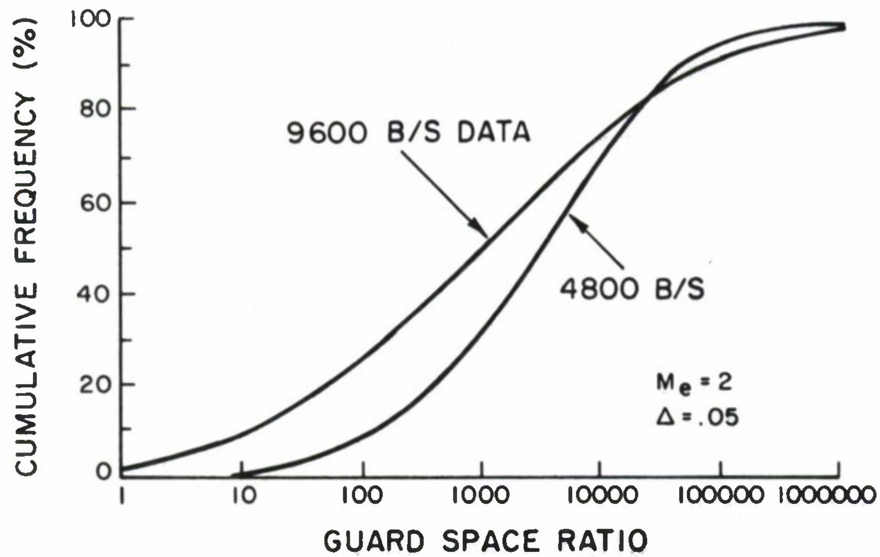

Figure 11. Cumulative Distribution of Interval to Burst Ratios

SECTION V

BLOCK CODING PERFORMANCE

The AUTOVON channel has been demonstrated to exhibit a long term bit error rate of 10^{-4} to 10^{-5} and long term block error rates ranging from 10^{-4} to 10^{-1} depending on the block size. For many applications, such as, transmission of command and control information or computer interconnection, error rates in these ranges may be unacceptable. The question, therefore, arises as to what percentage of the channel transmission capacity must be dedicated to error correction parity in order to reduce the error rates in delivered information?

BCH Error Correcting Codes

While there are large numbers of block codes, few block error correcting codes are better, in terms of the number of errors corrected for a given number of parity bits than Bose-Chaudhuri-Hocquenghem (BCH) codes. Thus, BCH codes are used to evaluate error correction performance. A BCH code is a cyclic code which for any integers m and t has $n=2^m-1$ bits in a code block of which $n-k \leq mt$ bits are parity bits (there are k information bits) and the minimum distance of the code is $d \leq 2t + 1$ (t bit errors can be corrected in any block of n bits).

The performance of BCH codes as a function of errors corrected (t) and code rate (k/n) is presented in Table II. If, for example, it were desired to use 95% of the data block for information then 5 errors could be corrected in a 1023 bit block, 3 errors in a 511 bit block and 1 error in a 255 bit block.

Table II can be used in conjunction with Figures 5 and 6 to estimate the performance of BCH codes on the AUTOVON channel data.

Table II

BCH Code Performance

Errors Corrected	Block Length (Bits)							
	7	15	31	63	127	255	511	1023
	Code Rate (k/n)							
1	.57	.73	.84	.90	.94	.97	.98	.99
2		.47	.68	.81	.89	.94	.96	.98
3		.33	.52	.71	.83	.91	.95	.97
4				.62	.78	.87	.93	.96
5			.35	.57	.72	.84	.91	.95
8				.29	.56	.75	.86	.92
16					.23	.51	.72	.84
24					.12	.36	.59	.77
32						.18	.47	.69
64							.15	.43
96							.06	.27
128								.12
160								.12
192								.04

At a block length of 1023 bits, the uncorrected channel block error rate at 4800 b/s is 10^{-2}. If 5% of the channel were used for parity, this uncorrected channel block error rate could be reduced to 10^{-3}. To achieve a 10^{-4} block error rate, it would be necessary to correct between 32 and 64 errors. This would require approximately 50% parity. Error-free transmission, requires the correction of all 128 errors (Figure 5 at a block length of 1023 bits) necessitating 88% parity. This results in an effective information rate of 0.12 x 4800 or 576 bits/second.

At 9600 b/s similar results can be read off of Figure 6. It is interesting to note that if 50% parity were used at 9600 b/s, the uncorrected block error rate would improve from 5×10^{-2} to 5×10^{-5} at 1023 bits per block. A 4800 b/s effective data rate could be achieved with an uncorrected block error rate of 5×10^{-5} instead of 10^{-2}. The 4800 b/s improvement factor in block error rate would be 200.

The figure of merit of forward error correction can be defined as the ratio of uncorrected block error rate to corrected block error rate multiplied by the code rate. If the figure of merit is unity then an even trade has been made between block error rate and code rate. If it is greater than unity then true net improvement has been achieved and if it is less than unity, the price in information data rate has been greater than the gain in reduced block error rate. As is evidenced in Tables III and IV, short block codes give little or no improvement in return for the parity which must be transmitted. Improvement generally increases with block length with a 511 bit block near optimum.

Table III

Forward Error Correction Performance (4800 b/s)

Errors Corrected	Block Length (Bits)							
	7	15	31	63	127	255	511	1023
	BCH Code Figures of Merit							
1	1.4	1.6	2.2	1.8	2.8	2.6	3.3	3.3
5			2.8	2.9	5.4	6.7	10.1	6.3
16					6.9	10.2	18	12
64							30	43

Table IV

Forward Error Correction Performance (9600 b/s)

Errors Corrected	Block Length (Bits)							
	7	15	31	63	127	255	511	1023
	BCH Code Figures of Merit							
1	.75	.76	.86	.91	.94	.97	.98	.99
5			7	8.5	7.2	9.3	9.1	9.5
16					46.	150.	144.	112.
64							1000.	860.

SECTION VI

CONCLUSIONS

The AUTOVON channel is a mixed error channel exhibiting both bursts and random errors. The duration of bursts is both time dependent and data rate dependent. Using block coding, the error rates on the channel can be decreased with improvement factors in the range of two orders of magnitude in error rate for equivalent information rates at block lengths that are reasonable for practical communication. However, to achieve error-free data transmission approximately 90% of the transmitted bits would have to be parity.

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2. K. Brayer, Error Patterns Measured on Transequatorial HF Communication Links, IEEE Transactions on Communication Technology, April 1968.